Smart Supply Chains for Agricultural Products: Key Technologies, Research Progress and Future Direction

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Abstract

[Objective/Significance] The intelligent transformation of agricultural product supply chains is a key pathway to solve the traditional problems of information gaps, high logistics costs, and difficult quality traceability. It is of great significance for improving efficiency, ensuring quality and safety, and agricultural modernization. This paper systematically analyzes its connotation, reviews technological progress in various links, and proposes development directions.

[Progress] This paper comprehensively reviews the research progress of key technologies in the smart supply chain of agricultural products across production, processing, warehousing, transportation, distribution, and sales links. The production link integrates Internet of Things (IoT), Artificial Intelligence (AI), and blockchain technologies to achieve precise decision-making and pest control; the processing link relies on intelligent sorting and new cleaning and sterilization technologies to improve quality; warehousing uses IoT monitoring and AI to optimize inventory management and improve efficiency; transportation focuses on cold chain technology innovation and intelligent scheduling system optimization for delivery efficiency; the sales end uses big data and AI technology to drive precision marketing and inventory management, with full-chain traceability ensuring data transparency.

[Conclusion/Prospects] The future requires accelerating unmanned operations and information sharing platform construction, enhancing supply chain resilience through technology empowerment, and promoting refined management to strengthen international competitiveness. In terms of industrial models, low-carbon transformation should be deepened, promoting clean energy, green packaging, and intelligent logistics to align with "dual-carbon" goals. Current technology applications still face challenges such as data governance and insufficient standardization, requiring policy guidance to establish technical standards, increase R&D investment, and strengthen cross-field collaborative innovation to promote intelligent upgrades, providing support for sustainable agricultural development and global food security.

Keywords: agricultural products; smart supply chain; Internet of Things; artificial intelligence; blockchain; dual-carbon

1. Introduction

Agricultural products, as fundamental materials for human survival and development, have supply chain stability and efficiency directly related to food safety, sustainable agricultural development, and farmers' vital interests. Traditional agricultural product supply chains encompass multiple links including production, processing, warehousing, transportation, and sales. Due to numerous links, complex scenarios, and strong time sensitivity, there are many problems such as information asymmetry, high logistics costs, and difficult agricultural product quality traceability.

With the rapid development of new-generation information technology and its widespread application in various fields, the intelligent transformation of agricultural product supply chains has become an inevitable trend of social development. This not only helps improve supply chain efficiency and ensure agricultural product quality and safety, but also meets market demand for high-quality agricultural products, further promotes increased production and income for farmers, drives the agricultural modernization process, and enhances the international competitiveness of China's agricultural products.

Currently, domestic and foreign scholars have conducted some research on the intelligent transformation of agricultural product supply chains. However, despite these studies exploring the intelligent transformation of agricultural product supply chains from different perspectives, there are still some shortcomings. First, there are relatively few comprehensive research results, with most studies focusing on specific technologies or links, lacking systematic sorting and comprehensive analysis of the entire intelligent transformation process. Second, the actual application cases and effect evaluations of emerging technologies in agricultural product supply chains are not deep enough, without in-depth exploration of the specific application scenarios and practical effects of emerging technologies such as blockchain and AI in supply chains. Additionally, there has been no systematic sorting of the key technology adaptability and comprehensive application paths of various links in agricultural product supply chains.

2. Connotation of Smart Agricultural Product Supply Chains

In 1982, Oliver Williamson, a representative figure of new institutional economics, first systematically proposed the term "Supply Chain" in his classic work "Markets and Hierarchies: Analysis and Antitrust Implications." This initial definition focused on analyzing organizational forms of inter-enterprise transaction relationships. Although it did not form a clear operational definition, it laid an important theoretical foundation for the construction of supply chain management theory systems.

After more than ten years of development, the Supply Chain Council (SCC) launched the milestone Supply Chain Operations Reference (SCOR) model in 1996, first clearly defining supply chain as "a network structure system centered on core enterprises, achieving integrated control from raw material procurement to end-user delivery through integration control of information flow, logistics, and capital flow," constructing a standardized management framework through five core processes: planning, procurement, production, delivery, and reverse logistics.

In the agricultural product field, agricultural product supply chains specifically refer to multi-entity chain network systems centered on primary agricultural products, consisting of production, processing, warehousing, transportation, distribution, and sales links. Combined

with global supply chain intelligent transformation practices, smart agricultural product supply chains can be defined as: supply chain innovative forms that rely on modern information technologies and intelligent equipment such as IoT, big data, blockchain, and AI, achieving precise production and processing, efficient logistics distribution, intelligent marketing services, and trustworthy quality traceability through full-process data collection, intelligent decision-making, and dynamic optimization.

3. Key Technologies in Various Links of Smart Agricultural Product Supply Chains

3.1 Key Technologies in Production Links

The production link in agricultural product supply chains, as the starting point of smart supply chains, involves multiple aspects including land and agricultural resource preparation, planting or breeding process management, field or breeding environment control, and harvesting. Currently, technologies such as IoT, big data, AI, blockchain, and remote sensing show great application potential in this link.

IoT Technology for Real-time Monitoring and Data Collection: IoT technology achieves real-time monitoring and data collection of environmental parameters such as soil moisture, temperature, light intensity, and pest conditions through various sensors deployed in farmland, providing scientific basis for subsequent agricultural production decisions.

Big Data Processing and Analysis Mining Technology: Big data technology provides comprehensive risk monitoring and resource optimization solutions for agricultural production by integrating massive data collected by IoT and using data analysis and mining techniques, assisting in precision agricultural decision-making.

AI-assisted Intelligent Decision Technology: Through integrating high-throughput phenotypic analysis, remote sensing technology, and wireless sensor networks, AI can analyze crop growth data in real-time, optimizing fertilization, irrigation, and pest management strategies.

Remote Sensing Technology for Macro Monitoring and Disaster Warning: Remote sensing technology obtains macro information of farmland through satellite or drone remote sensing platforms, such as crop growth, soil moisture, vegetation coverage, providing macro monitoring and disaster warning services for agricultural production.

Blockchain Technology for Data Transparency and Trust Assurance: Blockchain technology provides transparency and trust assurance for data recording and sharing in agricultural production links through its decentralized and tamper-proof characteristics.

3.2 Key Technologies in Processing Links

Following the production link, the agricultural product processing link is an indispensable part of smart supply chains, aimed at appropriate physical, chemical, or biological treatment of agricultural products, such as cleaning, sorting, grading, drying, and packaging, to extend their shelf life, optimize appearance, and facilitate subsequent storage, transportation, and sales.

New Cleaning and Sterilization Technologies: Traditional cleaning methods have problems such as incomplete cleaning and easy secondary contamination. Therefore, new cleaning and sterilization technologies have become research hotspots. For example, ultrasonic cleaning technology effectively destroys microbial cell walls through cavitation effects generated by high-frequency vibration, achieving deep cleaning of agricultural products.

Intelligent Sorting and Grading: Computer vision, hyperspectral imaging, near-infrared spectroscopy, deep learning, and robotics are used to achieve intelligent grading and sorting, defect detection, nutritional assessment, and packaging of agricultural products.

3.3 Key Technologies in Warehousing Links

The warehousing link serves as an intermediate bridge in agricultural product supply chains, closely connected to the processing link, playing a key role in connecting preceding and following stages, responsible for proper storage and custody of processed products, ensuring their quality and safety, and laying the foundation for subsequent transportation and sales.

IoT Technology Applications: Using IoT technology, real-time monitoring of parameters such as temperature, humidity, and gas concentration in warehouses, as well as freshness and pesticide residues of agricultural products, ensures product quality and safety.

AI Technology for Inventory Optimization: AI technology can optimize warehouse allocation through spatial mapping genetic algorithms, reducing warehousing costs and time. Machine learning is used to solve stockout prediction problems in inventory control, effectively reducing enterprise stockout risks.

Robotics Technology: Handling robots and palletizing robots can achieve automated retrieval, handling, storage, and palletizing tasks, significantly improving handling speed and picking accuracy while reducing labor costs.

3.4 Key Technologies in Transportation Links

The transportation link serves as a key link in agricultural product supply chains, closely connected to the warehousing link, jointly ensuring smooth circulation of agricultural products from production to consumption. Research on key technologies in transportation links focuses on temperature control in cold chain transportation, safety protection of agricultural products in transit, optimization of intelligent transportation scheduling systems, and application of new energy vehicles.

Cold Chain Transportation Technology: Research and application of more precise and stable cold chain transportation technologies, such as intelligent temperature control systems and phase change materials, improve temperature control accuracy and stability of agricultural products during transportation.

Intelligent Transportation Scheduling Systems: Establish unified information platforms and data standards, promote information sharing and collaborative operations among different transportation enterprises, warehousing facilities, and agricultural product suppliers.

3.5 Key Technologies in Distribution Links

The distribution link serves as the "last mile" of agricultural product supply chains, closely

connecting with warehousing and transportation links. Research shows significant progress in route optimization, in-transit control, and personalized services through various optimization algorithms and intelligent technologies.

3.6 Key Technologies in Sales Links

The sales link is closely connected to the distribution link, jointly forming the final bridge from production areas to consumers. Big data analysis and AI technologies are used for market analysis, achieving demand forecasting, price optimization, and precision marketing.

3.7 Trustworthy Supervision and Traceability Technology

Trustworthy supervision and traceability technology runs through all links of agricultural product supply chains, from production and processing to warehousing, transportation, and sales, ensuring accurate data recording and transparent, traceable information in every link.

4. Challenges and Recommendations for Emerging Technologies in Smart Agricultural Product Supply Chains

4.1 AI Technology Challenges

- **Data Governance System Defects:** Structural defects in data governance systems, with heterogeneous data formats and non-unified collection standards
- **Technology Integration Bottlenecks:** Compatibility obstacles between AI algorithms and heterogeneous hardware systems
- **Standardization Lag:** Lack of standardization frameworks across levels

4.2 Robotics Technology Challenges

- **Perception and Recognition Accuracy:** Need for improvement in complex and variable working environments
- **Operation Flexibility:** Need for enhancement in precision operations
- **Communication and Collaboration Capabilities:** Need for improvement in coordinated work

4.3 New Energy Technology Challenges

- **High Initial Investment Costs:** High procurement costs for new energy equipment
- **Technology Stability:** Susceptibility to natural factors affecting continuous operation
- **Infrastructure Support Deficiencies:** Incomplete supporting facilities

4.4 New Materials Technology Challenges

- **Performance vs. Cost Contradictions:** Bio-based degradable plastics have performance limitations
- **Safety and Effectiveness Verification:** Long-term health impact uncertainties
- **Information Accuracy and Durability:** Sensor interference and material durability issues

5. Future Development Directions for Smart Agricultural Product Supply Chains

5.1 Unmanned Operations in Operational Processes

Unmanned operations in agricultural product supply chains are inevitable choices to address labor shortages, improve industrial efficiency, and standardization. Future development should cover the entire chain from planting, processing, warehousing to transportation, relying on high-precision sensing, intelligent algorithms, and automation equipment.

5.2 Lean Management Systems

Lean management of agricultural product supply chain management systems is an inevitable choice for improving resource utilization efficiency, ensuring product quality, and enhancing market competitiveness. The vision is to achieve efficient operation and overall benefits through comprehensive information sharing platforms and optimized supply chain processes.

5.3 Low-carbon Industrial Models

Low-carbon transformation of agricultural product supply chains is the core path to address

climate change and achieve sustainable agricultural development. Through clean energy applications, resource recycling, and full-process carbon footprint control, construct low-consumption, high-efficiency, and eco-friendly supply chain systems.

Conclusion

Smart agricultural product supply chains represent the future direction of agricultural development, requiring coordinated breakthrough in "technology-management-model" dimensions. Through systematic solutions including unmanned operations, lean management, and low-carbon models, the comprehensive intelligent upgrade of agricultural product supply chains can be achieved, ultimately contributing to agricultural modernization and sustainable development.

Conflict of Interest Statement: This research has no conflicts of interest involving researchers and publicly disclosed research results.

Citation format: HAN Jiawei, YANG Xinting. Smart Supply Chains for Agricultural Products: Key Technologies, Research Progress and Future Direction[J]. Smart Agriculture, 2025, 7(3): 1-16.